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REPORT OF THE SCIENCE WORKING GROUP:

SCIENCE WITH A LUNAR OPTICAL INTERFEROMETER

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Resolution is the single greatest constraining parameter in observational astronomy. The Earth's atmosphere causes an optical image to blur to about 1 arcsec or greater, which is significantly larger than the diffraction limit of most optical telescopes. Interferometric techniques have been developed to overcome atmospheric limitations for both filled-aperture conventional telescopes and for partially filled aperture telescopes, such as the Michelson interferometer or the radio interferometer. Small apertures (from isoplanatic constraints) and the inherent complexities associated with image restoration have limited the use of ground-based optical interferometry to the brightest celestial objects. Current estimates suggest that practical limits to ground-based interferometry will constrain possible resolution to the 1 - 100 mas range. Background seismic noise will prevent any further gains in resolution even if the atmospheric problems are solved.

The Hubble Space Telescope (HST) represents the first step toward space-based optical astronomy, away from the shackles of the Earth's atmosphere. The expected resolution is typically 0.1 arcsec, about an order of magnitude improvement over direct ground based imaging. This improvement is expected to bring out a revolution in optical astronomy as evidenced by the activities of many HST working groups and by the publication of many reports on the potential science windfall. The HST represents an immediate short-term evolution of observational optical astronomy.

In this paper, we wish to focus on a longer time scale of evolution and consider the benefits to astronomy of placing an array of telescopes on the Moon at a time when a permanent base may exist there. The advantages of going to the Moon rather than observing from Earth orbit or one of the Langragian points are based on considerations of background emissions and engineering constraints. These advantages are summarized in the reports of the other two working groups in this workshop. Given the low level of seismic activity on the Moon, the lack of any appreciable atmosphere, and the stability of the lunar soil, it is possible to speak of 10-km interferometer baselines, corresponding to an angular resolution of 10 mas in the middle of the optical spectrum.

Figure 1 summarizes the science made accessible by increasing the angular resolution. Although the HST will open great new areas of research, these represent only the tip of the iceberg. Furthermore, close inspection of figure 1 reveals a natural boundary at 1 mas, beyond which lies a vast amount of unexplored science. This boundary, as mentioned previously, corresponds to a limit on future ground-based imaging. It is the astronomy beyond this limit we wish to discuss here, with the aim of providing the scientific justification needed for establishing an observatory on the Moon.

Basic Working Parameters

It is not the aim of this paper to discuss engineering aspects regarding the feasibility of an optical array capable of microarcsecond scale resolution (this problem is discussed separately in the proceedings). We will assume that the array is sensitive to angular scales in the 1 to 1000 mas range.) The sensitivity is assumed to correspond to a 50-m^2 collecting area, roughly equal to that of the next generation ground-based telescopes. For reasonable integration times (of order ≈1 hour) we are assuming a working magnitude limit of $\approx 30^m$/pixel. Beyond this limit it is necessary to consider such effects as the zodiacal light and the galactic background, which is outside the scope of this paper. A further assumption, based on the science discussion below, is that the interferometer will nominally operate in the 0.1 μm - 10 μm wavelength range.

As with any interferometer there is a tradeoff between field of view (FOV) and the sensitivity of signal-to-noise ratio (SNR). The FOV can most generally be expressed as

$$FOV = \theta_R \frac{\lambda}{\Delta\lambda},$$

where θ_R is the resolution angle and $\Delta\lambda$ is the bandwidth of the signal being correlated. In the limit where the SNR depends only on the fluctuations of the detected signal (i.e., photon counting case), the SNR can be expressed as

$$SNR = \frac{S}{\sigma_s} = \sqrt{<L>},$$

where $<L> \propto \tau\Delta\lambda$ is the number of photons integrated over time and bandwidth. The scaling factor is such that $0^m = 10^3$ photons/cm^2/s/Å. A comparison between the two equations shows the inverse relationship between FOV and SNR. For example, a $\Delta\lambda$ of 10^3 Å (good sensitivity) corresponds to an FOV of 10 mas for θ_R of 10 mas, roughly the same scale size as the diffraction size of a 5-m mirror. The FOV is therefore a major constraint on studies of faint extended objects. To get around this problem, it will be necessary to utilize multichannel correlators.

With these working constraints in mind we now ask ourselves the question, "What science can be done with a lunar optical interferometer?"

The Science

Although there are a number of obvious, specific observations one can immediately list, we have chosen instead to group such observations under more general but important astrophysical questions. We address here seven such questions which can only be directly addressed through mas microarcsecond scale observations. Each problem is discussed in terms of specific relevant observations and how such observations contribute collectively to an understanding of the problem.

What is the nature of the engine that powers active galactic nuclei?

The relevant observations that will best address this question include accretion disk morphologies, location and morphologies of inner jets, and the details of the environment that both fuels the source and constrains the energy outflow. At resolutions of 1 - 10 mas, it is possible to directly image accretion disks in active galactic nuclei (AGNs) such as Centaurus A and M87. In the case of Centaurus A, it is possible to "see" down to the Schwarzschild radius of a 10^8 solar mass black hole. The orientation of the accretion disk and the measurement of its inner and outer dimensions would provide powerful contraints for models of the central engine. A spectral analysis of the immediate environment should provide information on how the accretion disk is fueled. Kinematic information may shed light on the hydrodynamics of the process by which the inflow is converted into collimated outflow. Moreover, observations of the inner jets should further define the nature of this process. The ultraviolet portion of the spectrum is ideal for this kind of study because it provides optimal resolution and avoids self-absorption effects, expected to be important at longer wavelengths.

Detailed imaging of the stellar populations of AGNs will directly address questions regarding starburst galaxies and the Seyfert phenomenon. It may also provide direct evidence for stellar collisions and tidal disruption of stars near supermassive black holes.

What is the physics of collapsed stellar objects?

Observations of interacting binary stars in which one star is a collapsed object (e.g., X-ray binaries) may provide important informatin on the frequency of white dwarfs, nuetron stars, and black holes. It may also shed light on the mass transfer mechanism in such binaries.

For typical X-ray binaries in the galaxy, features on the scale of lengths of a solar radius (10^{11}- cm) can be resolved. This should be sufficient to image accretion disks and locate such features as hot spots. Since the mechanisms that trigger novae and type I supernova explosions are thought to involve mass transfer onto compact objects, detailed mapping of the accretion disks and any associated material will be of direct relevance to this problem. Furthermore, the mechanisms by which mass is transferred, whether by Roche lobe overflow or focused stellar winds, can be directly tested by such observations.

What is the relationship between the Sun and other stars, the so called solar-stellar connection?

Observations of surface features, rotation rates, and probing of internal structure are all directly relevant when comparing the Sun with other stars, particularly those of the same spectral class. Solar-type stars can be resolved to distances of ≈ 1 kpc. A systematic study of a large number of such stars may provide important information on the time-line of solar-type activity. This would enable us to infer the history of solar activity and to predict long term secular changes in the Sun. Such information is relevant for determining habitation zones around solar-type stars. In the case of our Sun, informatin on the evolution of such zones may give us considerable insight into the effects of solar activity on the evolution of life on Earth.

Direct measurements of rotation rates (from motion of surface features) of solar-type stars of different ages will allow us to infer the angular momentum history of our Sun and stars like it. The importance of mass loss and planetary systems in changing the angular momenta of solar-type stars can be addressed through this kind of study.

Stellar seismology utilizes spectroscopic techniques to probe stellar interiors. Such studies would be greatly enhanced for spatially resolved stellar disks and would allow comparisons of stellar structure and the long term evolution of the interiors of solar-type stars.

What environmental factors govern the star formation process?

The shape of the luminosity function of recently formed stars, morphology of protostellar systems, and their local environment are important observations that can define the characteristics of the star-forming enviornment. Those characteristics that determine the initial mass function (IMF), the formation of single and double stars, and the formation of planetary systems are the ones that need to be identified.

Since star-forming regions (SFRs) are highly obscured, IR observations will be of greatest value. At a resolution of 100 mas (at say 5 μm) it should be possible to resolve protostars in nearby SFRs such as the Orion nebula. Given sufficient sensitivty, protoplanets of Jupiter's size could be studied individually, thereby shedding considerable light on the process that governs the formation of planetary systems.

Studies of outflows associated with young stellar objects can be made on scales of 0.1 - 1 solar radii, so that a much more detailed picture can be painted of the evolution of stars on their way to the main sequence.

The observations of young clusters in nearby galaxies can be used to infer how the IMF changes with position (and therefore environment) in a galaxy. Such studies can be extended to determine how the star formation process varies from one type of galaxy to another.

Do other planetary systems exist?

This question can be most directly addressed through imaging of the surroundings of nearby stars. However, such imaging is more difficult than it would seem because of dynamic range considerations and the restricted FOVs of optical interferometers operating at high resolution. The Sun and Jupiter, for example, would form a pair that at a distance of 10 pc would have magnitudes of 5 and 26 respectively and be 0.5 seconds of arc apart. The Earth would be 0.1 arcsec away and have a magnitude of 30. The interferometer, operating at a resolution of 10 mas, would have a field of view of only 10 mas. Unless one knew where to look, planets would be very difficult to find. The use of narrow band filters would solve the FOV problem but decrease the sensitivity of the interferometer. Again, multichannel correlators are desired for this kind of work. The IR may provide an easier way to detect planets because the magnitude difference between a star and Jupiter-like planets is reduced to 18 magnitudes in the N band, for example.

For the nearest stars, Jupiter-like planets could actually be resolved with as many as 100 resolution elements across thier disks. Once found, planets could be analyzed spectroscopically to determine atmospheric compositions, crucial in determining habitability.

How do galaxies form?

Dynamic information from the motions of stars and gases can be used to infer the angular momentum distribution in the central and disk regions of galaxies. These distributions provide crucial tests for models of galaxy formation.

By combining proper motion measurements of stars with their radial velocities, it is possible to determine their 3-D velocities as they move in the gravitational potential of a galaxy. Such measurements can be made for the nearest galaxies. For stars near the center of a galaxy, information on the localized mass distributions may lead to the discovery of black hole nuclei in galaxies like M32 and M87. Stellar disk dynamics will allow a comparison of the angular momentum distributions of disks of varying Hubble types. Comparisons among spirals and between spirals and ellipticals may shed light on the manner in which galaxies formed and the differences in initial conditions that led to the currently observed differences.

Similar studies of the internal dynamics of globular clusters can be used to probe their likely formation processess. The dymanics of galactic bulges and the nature of the triaxiality of elliptical galaxies can also provide clues on the formatin of galaxies.

Is the Hubble flow uniform and isotropic?

Astrometry on mas scales can, over a time-line of 1 to10 years, measure proper motions corresponding to velocities of $\approx$ 100 km/s at a distance of 100 Mpc. This corresponds to 2-4 percent of the Hubble flow velocity. Since proper motions measure velocities at right angles to the line of sight, any such motions would represent a deviation from a purely Hubble flow. A test of this uniformity at the 2 percent level would be crucial in better understanding the evolutin of the universe.

Dynamics of nearby clusters of galaxies can be analyzed in three dimensions to determine whether such clusters are bound. The answer to that question bears directly on the nature of dark matter and the overall geometry and evolution of the universe. Finally, the use of gravitational microlensing as a diagnostic of line of sight material may be useful in mapping the small-scale structures.